Douglas A. Ducey
Governor

Henry R. Darwin
Director

via e-mail

June 22, 2015
FPU15-273

Ms. Catherine Jerrard
AFCEC/CIBW
706 Hangar Road
Rome, NY 13441

RE: WAFB – *ADEQ Evaluation of USAF Response to ADEQ Comments; Weekly Progress Report April 27, 2015* and *Progress Report May 4, 2015*; *Steam Enhanced Extraction at the Former Williams AFB, ST012 Site, Mesa, AZ*; ADEQ document dated May 14, 2015

Dear Ms. Jerrard:

Arizona Department of Environmental Quality (ADEQ) Federal Projects Unit (FPU) and ADEQ contractors UXO Pro, Inc. and Praxis Environmental Technologies reviewed the above-referenced document. Praxis Environmental Technologies evaluated the U.S. Air Force Civil Engineering Center (AFCEC) responses. Italicized text presents the Air Force response. Following text, tables, and/or figures provide Praxis evaluation, clarification information, and/or rebuttal.

EVALUATION

ADEQ E1) Responses to Comments 1, 2, 3, 4

For hydraulic containment during steam injection, the following mass balance relationship applies,

(Extraction Rate) > (Injection Rate + GW Encroachment + Steam-Displaced Groundwater)

$$\dot{m}_{extract} > \dot{m}_{inject} + \dot{m}_{encroach} + \dot{m}_{displace}$$

$$\frac{\dot{m}_{extract}}{\dot{m}_{inject} + \dot{m}_{encroach} + \dot{m}_{displace}} > 1$$

The mass displacement rate is a function of the growth rate of the steam zone and accounts for phase change according to energy and volume balances. The encroachment accounts for natural groundwater flow. The injection parameter accounts for steam condensate.

Because the steam condenses, there is no reliable way to calculate or measure the actual steam volume in the formation.

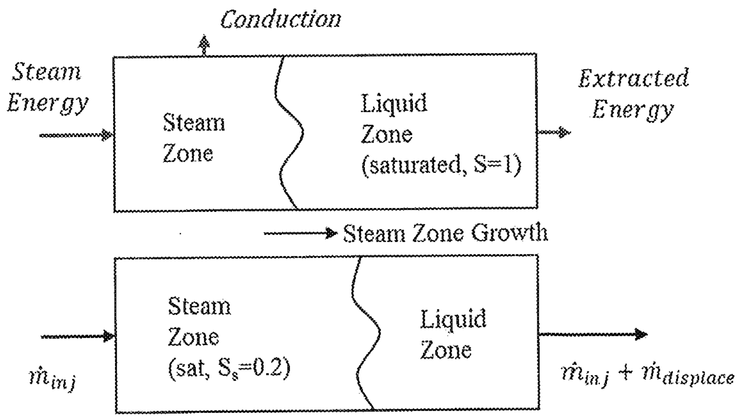
This is contradictory to the statement in the SEE Work Plan, Appendix D, p10,

> "The injection of steam is a stable and predictable process. The steam propagation is governed by heat transfer to the formation, which has been studied intensively for oil recovery and has been applied to remediation applications for over 20 years."

A straightforward method to estimate steam zone volume and growth during injection is provided in the attached document, "Evaluation of Hydraulic Containment during Steam Enhanced Extraction." The method has been published in numerous references over the last 50 years (e.g., Marx & Langenheim, 1959; Mandl & Volek, 1969; Yortsos, 1982; Menegus & Udell, 1985). Application of the method to ST012 is also provided in the TEE Pilot Study Work Plan, Appendix C and in the TEE Pilot Study Evaluation Report, Appendix I. Use of the method as input to MODFLOW for assessing hydraulic containment is provided in the TEE Pilot Study Evaluation Report, Appendix H.

The method includes energy injection, energy extraction, and thermal conduction into fine-grained confining layers and combines mass and energy balances to estimate the growth of the steam zone and the rate of groundwater displacement during growth. As described in the cited attachment, combined mass and energy balances yield a single equation,

$$\frac{\dot{m}_{displace}}{\dot{m}_{inj}} = \frac{(1-S_S)\left[1+\dfrac{h_{fg}}{c_{pw}(T_S-T_0)}\right](1-F_{ext}-F_{cond})}{\dfrac{\rho_r c_{pr}(1-\varphi)}{\rho_w c_{pw}\varphi}+S_S+(1-S_S)\dfrac{\rho_v}{\rho_w}\left[1+\dfrac{h_{fg}}{c_{pw}(T_S-T_0)}\right]} - 1$$



F_{ext} and F_{cond} represent energy extraction and thermal conduction rates, respectively, relative to the energy of steam injection. As provided in the attachment, substituting LSZ-specific parameters into this equation yields an expression for hydraulic containment during steam injection,

$$\frac{\dot{m}_{extract}}{\dot{m}_{inj}+\dot{m}_{encr}+\dot{m}_{inj}[2-3(F_{ext}+F_{cond})]} > 1$$

TerraTherm considers a ratio of 1.25:1 to be a minimum and prefers to operate at ratios of 1.5:1 and higher.

Data from weekly progress reports were used as input into the mass ratio expression above. Separate calculations for the LSZ and UWBZ were performed with data and parameters approximated from Figure 17 and Figure 21. The parameters and results are provided below. As indicated, initial extraction rates were much lower than required to contain the applied steam injection rates. Containment conditions are improved recently as a result of energy extraction but hydraulic containment has not been maintained in either zone during the operating conditions shown below. On 6/1/15, the LSZ extraction rate required to achieve a net ratio of 1.5 in the LSZ was about 120 gpm (205 gpm overall) and on 6/8/15 the LSZ extraction rate needed to be about 150 gpm (275 gpm overall) for hydraulic containment during the reported steam injection rates. However, the assumed thermal conduction rates are likely overpredicted.

Mass & Energy Balances for Hydraulic Containment

Week	Extraction $\dot{m}_{extract}$	Injection $\dot{m}_{inject}$	GW Flow $\dot{m}_{encroach}$	F_{ext} $\dot{E}_{ext}/\dot{E}_{inj}$	Displace $\dot{m}_{displace}$	Net Ratio
OVERALL	(incl CZ ext)					
11/23/14	126	66	12	0.05	82	**0.79**
12/1/14	129	65	12	0.08	75	**0.85**
12/8/14	161	72	12	0.07	85	**0.78**
12/15/14	142	75	12	0.09	86	**0.82**
6/1/2015	120	73	12	0.40	36	**1.00**
6/8/2015	101	70	12	0.25	66	**0.68**
LSZ						
11/23/14	82	66	7.5	0.05	82	**0.53**
12/1/14	81	65	7.5	0.08	75	**0.55**
12/8/14	85	64	7.5	0.09	72	**0.59**
12/15/14	96	61	7.5	0.11	66	**0.72**
6/1/2015	70	49	7.8	~0.40	24	**0.86**
6/8/2015	55	48	7.8	~0.25	45	**0.55**
UWBZ						
12/8/14	28	15	4.2	0.00	21	**0.70**
12/15/14	31	14	4.2	0.00	20	**0.79**
6/1/2015	41	23	4.2	~0.40	11	**1.06**
6/8/2015	38	23	4.2	~0.25	21	**0.79**

Values listed are in gallons per minute equivalent based on a water density of 8.35 lbs/gallon
$\dot{m}_{displace} = \dot{m}_{inj}[1.4 - 3F_{ext}]$ for 20% conduction during early steam injection
$\dot{m}_{displace} = \dot{m}_{inj}[1.7 - 3F_{ext}]$ for 10% conduction at later times when clays are heated

ADEQ E2) Responses to Comments 5 and 6

LSZ10, LSZ23 LSZ09 and LSZ27 are in upgradient locations of the site and do not pose similar potential for downgradient off-site migration.

Steam injection continued in LSZ09 although LSZ37 was not operating and required repair. The lack of extraction and containment in LSZ37 likely resulted in the NAPL accumulation in W30, upgradient of both the TTZ and HZ.

Similar adjustments may be made at LSZ18 and/or LSZ22 based on temperature increases at TMP2.

The benzene concentration in W34 is rising, well beyond the TTZ and HZ supporting the original comment to consider reducing or terminating injection at LSZ18 and reducing injection in LSZ22.

ADEQ E3) Response to Comment 7

Only limited steam breakthrough has occurred in the LSZ to date, so contaminant mass removal has not likely peaked.

According to the most recent weekly progress report (Table 4), steam is currently present in 8 of the 27 LSZ extraction wells and steam has appeared previously in an additional 10 of the wells. 18 of 27 LSZ extraction wells have experienced steam breakthrough.

ADEQ E4) Response to Comment 8

Has steam injection been reduced accordingly in nearby injection wells LSZ09 and LSZ23? No.

As stated above in Comments 5 and 6, the lack of extraction and containment in LSZ37 has likely caused the NAPL accumulation in W30, upgradient of the TTZ and HZ.

ADEQ E5) Responses to Comments 11 and 12

modification to remove the data [average zone temperatures in Figure 6] from earlier dates would result in discrepancies between the reports.

Excluding data from the calculation of averages going forward created a discrepancy and makes the plots flawed because the early averages are based on different temperature readings than more recent data. Presenting averages calculated from identical locations as suggested in the original comment is the only way to avoid discrepancies. For example, abruptly re-introducing a reading at steam temperature results in an increase in average that did not occur, or vice versa. The discrepancy was acknowledged in the AF response:

While addition of TMP13 back into the average temperature calculations contributes to the increases, the recent increases are real due to the increased steam injection that occurred during the period.

ADEQ E6) Response to Comment 13

Yes, heating by thermal conduction is a slow process and can only migrate 5-10 ft into tight layers during the duration of a steam project.

This response is in good agreement with the analysis provided above to support the original Comments 1-6. The rate of energy utilization by thermal conduction is very small in comparison to the rate of energy injection by steam; rendering a mass ratio of 1.5:1 or even 1.25:1 inadequate for hydraulic containment of mobilized NAPL.

ADEQ E7) Response to Comment 18

Yes, the uniformity of the temperature profile from 215 to 225 ft bgs suggest the steam zone is in the vicinity of this TMP

The temperature profile at TMP-10 continues to increase in the vertical extent of the steam zone, particularly at 225 ft bgs, indicating steam continues to flow to and beyond this location. Any mobilized NAPL in the direction of TMP-10 migrates with this steam flow. Steam injection should be reduced if not terminated at LSZ25.

ADEQ E8) Response to Comment 19

TMP11 has a slight temperature increase at 175 ft bgs (currently around 50 C). This is probably due to influence by the nearby injection well UWBZ16 (80 ft away) and is expected.

Figure 8 in the June 15, 2015 Weekly Progress Report shows 90 C at a depth of 170 ft bgs indicating the steam zone is very soon to arrive and move past this location far beyond the TTZ and beyond the defined HZ of the UWBZ. No mechanism exists to recover NAPL mobilized away from the TTZ in this area.

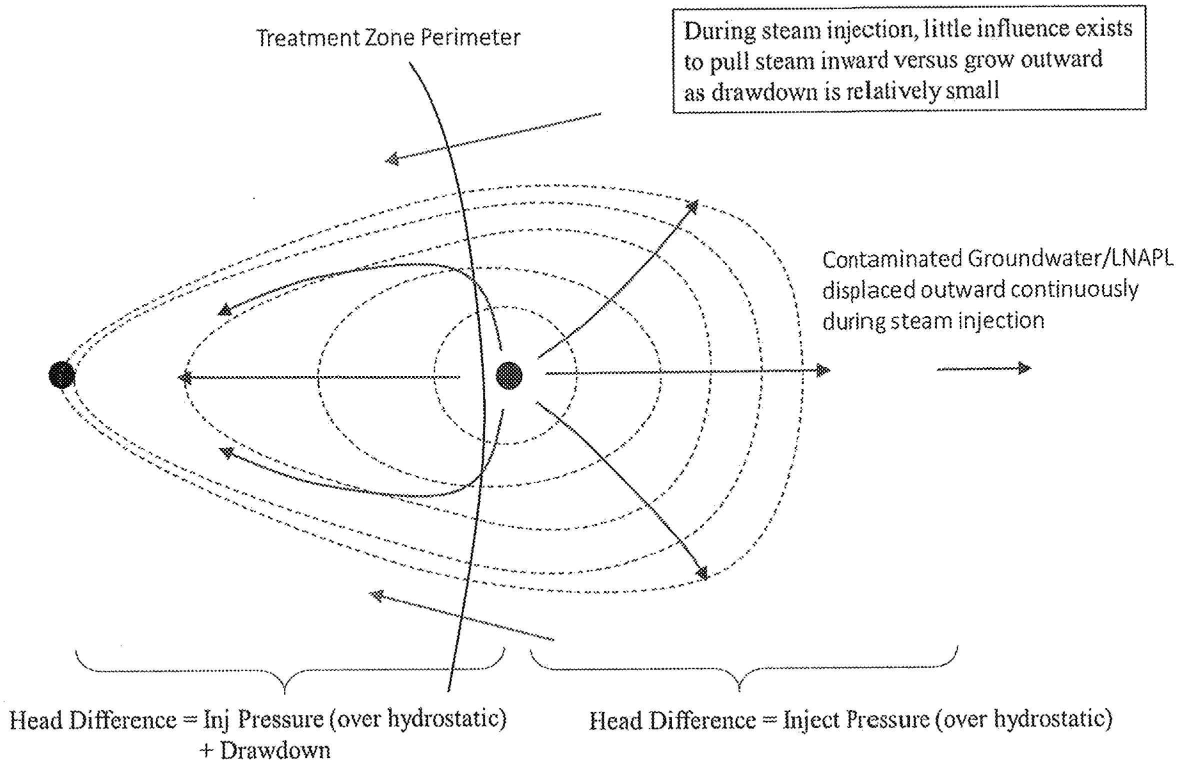
ADEQ E9) Responses to Comments 20, 22 and 23

We are currently building up the steam bubble in the UWBZ. The operational plan for the site is for perimeter steam injection wells to sweep steam out and around the injection wells and push inward to the outermost extraction wells (TerraTherm Design for SEE Treatment). Once we have steam breakthrough at the MPE wells, we will initiate pressure cycling where the steam bubble will be allowed to collapse or partially collapse, an inward gradient will be created.

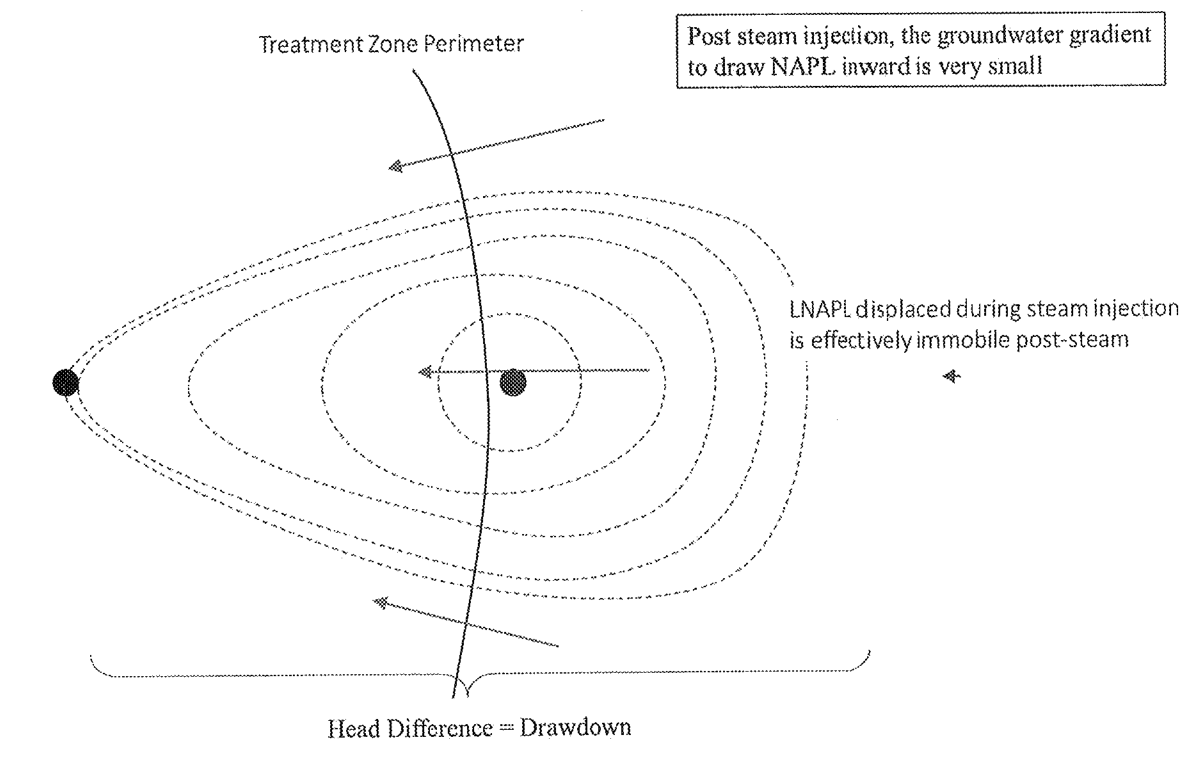
No mechanism or sufficient pressure gradient exists or will exist to recover NAPL mobilized away from the TTZ. Consider the pressure gradients illustrated below,

During steam injection, the drawdown pressure is small compared to the injection pressure and therefore only a small influence exists to pull the steam zone inward versus grow outward. Similarly, the steam zone pressure gradient to push mobilized NAPL at and beyond the TTZ perimeter is large compared to the extraction well gradient to draw the NAPL inward. When steam injection is ceased, the pressure gradient exerted by the drawdown and the collapsing steam zone is much smaller than the applied steam injection pressure gradient. As a result, NAPL pushed outward will not be pulled inward to extraction wells, the inward pressure gradient will be much smaller than the previous steam outward gradient. This rationale applies to perimeter injection in both the LSZ and UWBZ.

Perimeter Steam Injection



Post Steam Injection



ADEQ E10) Response to Comment 21

a substantially higher amount of water is extracted than injected from the UWBZ.

As demonstrated by the analyses accompanying Comments 1-6, the reported ratios of mass extracted to mass injected are insufficient for hydraulic containment after accounting for groundwater influx and water displaced by the growth of the steam zone.

ADEQ E11) Response to Comment 25

Yes, inflow conditions and hydraulic containment near the western boundary are monitored by perimeter monitoring wells U11, W11, W30, W12 and U12. Temperature monitoring of the western boundary is monitored by TMP 3, TMP 8 (although both TMPs are within the TTZ for the LSZ) and monitoring wells U11, W11, W30, W12 and U12... monitoring wells W30, W12 and U12 have not shown significant increases in temperature.

TMP-3 and TMP-8 indicate a steam zone in the TTZ and provide no data for assessing the growth of the steam zone beyond the TTZ or HZ in the southwest corner. The detection of the steam zone provides no information on the flow rate of steam through the location.
LSZ37 continues to yield steam temperatures across the extraction interval and provides no information on the flow rate of steam beyond this location.
The temperature readings in perimeter wells are not collected at ideal depths:

U11=128' (too shallow by ~50 feet)
W11= unknown
U12=185.71' (too deep by ~10-15 feet)
W12= 238.16' (too deep by ~10 feet)
W30=134' (too shallow by ~40 feet)

The recent NAPL accumulation in W30, upgradient of the TTZ and HZ, is likely caused by the lack of extraction and containment in LSZ37 and continued injection in LSZ09.

ADEQ E12) Response to Comment 26

inflow conditions, hydraulic containment, and temperature monitoring along the northern boundary are monitored by groundwater monitoring wells W12, U12, W36, U02 and W34.

See above for U12 and W12. Benzene concentrations are increasing in W34 and W36, well beyond the TTZ and HZ, and contrary to expectations for a groundwater inflow toward the TTZ.
The temperature readings in perimeter wells are not collected at ideal depths:

U02=185.03' (too deep by ~10-15 feet)
W34= 235.91' (too deep by ~10 feet)
W36=165' (too shallow by ~60 feet)

ADEQ E13) Response to Comment 28

The estimated inflow values under ambient conditions can be used to estimate revised ratios. The volume of the steam bubble cannot be measured. Both the ambient groundwater flow and the steam bubble growth were considered during the design and are accounted for in the target water mass extraction ratios. Encroachment and displacement are accounted for by the net water balance and the perimeter groundwater elevation data for hydraulic containment.

The volume of the steam bubble can be estimated using the straightforward analysis accompanying Comments 1-6. The analysis indicates the stated mass ratio of 1.5:1, or even 1.25:1, are inadequate for hydraulic containment during steam injection. In addition, an estimate for the stream zone volume should be available from the model described in Appendix D of the SEE Work Plan.

ADEQ E14) Response to Comment 29

Per the model, the temperatures within the treatment zone were expected to be at boiling after approximately 230 days of operation (under the given design assumptions) after the injection of approximately 230 million lbs of steam. To date, a total of approximately 140 million lbs of steam has been injected – substantially less than required to bring the entire TTZ up to steam temperatures.

The description of modeling and its results in Appendix D of the SEE Work Plan do not provide the estimate for energy extraction during the steam injection and therefore, the mass of steam injected to heat the soil to steam temperature cannot be assessed based solely on a total number (i.e., 230 million lbs of steam) without subtracting the energy extracted. The extraction rates are much lower than modeled and therefore the energy extraction is also likely much lower than modeled resulting in a lower absolute steam injection requirement. See Comments 1-6. Also, the energy balance provided under separate cover indicated much less net energy in the subsurface is required to bring the TTZ to steam temperature.

ADEQ E15) Response to Comment 30

The data required to provide energy balances for individual treatment zones are not available at this level of detail.

As shown in the analysis accompanying Comments 1-6, hydraulic containment should be assessed for the individual zones. Hydraulic containment in each zone is intimately related to the energy injection and extraction in each zone. Further, to date the extraction of groundwater in the Cobble Zone has been included in the overall mass ratio calculation. Such extraction has inconsequential impact on hydraulic containment in the LSZ and UWBZ during steam injection in those zones.

ADEQ E16) Response to Comment 31

The water levels measured in the perimeter wells during SEE are the result of the combined effect of the injection and extraction including the presence of the steam bubble within the TTZ. While the pressure gradients in the steam zone and the water saturated zone may be different, for hydraulic containment we are interested in the combined effect of the pressure gradients around the perimeter where only the saturated soil condition is present.

As stated in the response, the steam zone exists in the TTZ and beyond, and influences the water levels measured in perimeter wells during SEE. The second statement in the response is contradictory, the steam zone influences the perimeter water level readings whether saturated soils surround the perimeter wells or not.

ADEQ E17) Response to Comment 32

The volume of NAPL detected does not necessarily correlate with a direction of travel. Given that NAPL historically existed at both of these wells before SEE, NAPL presence/volume is not assumed to indicate a loss of containment. Hydraulic gradients are a better measure by which to evaluate hydraulic containment.

See Comment 31 above for an explanation as to why hydraulic gradients are not a better measure to evaluate hydraulic containment than a combined mass and energy balance by zone. The historic presence of NAPL at a location indicates a historic connection between that location and the source zone while the lack of historic presence may suggest a lesser connection. It is logical to presume that NAPL mobilized during SEE would travel along similar historic paths resulting in persistent accumulations such as those observed at W37, W11 and now W30. Similar logic applies to increasing benzene concentrations in groundwater.

Qualifier

This evaluation was based on information and knowledge available to ADEQ and its contractors. ADEQ may add or amend our evaluation if evidence to the contrary of our understanding is presented; submitted or received information is determined to be inaccurate or misinterpreted; if any condition was unknown to ADEQ at the time this document was signed; or if complementary regulatory agencies bring valid and proven concerns to our attention.

Closure

Thank you for the opportunity to evaluate your responses. Should you have any questions regarding this correspondence, please contact me by phone at (602) 771-4121 or e-mail miller.wayne@azdeq.gov.

Sincerely,

Wayne Miller

Wayne Miller
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Waste Programs Division

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